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TOWING TANK STUDIES OF STRATIFIED FLOW OVER RIDGES AND VALLEYS

by

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16. ABSTRACT

Stable atmospheric flow over a ridge and a valley was simulated in a large towing tank filled with stratified salt water. Flow visualization experiments were conducted using colored dye streamers and 10 cm high models with sinusoidal cross-sections. These experiments provided qualitative data on the structure of the flow field over the ridges and within the valley. They also provided quantitative data on the height of the dividing streamline which separates the fluid that flows over a ridge from that which flows around the ends. These data agree with an existing theory based upon the potential energy barrier associated with flow over the ridge.

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1. INTRODUCTION

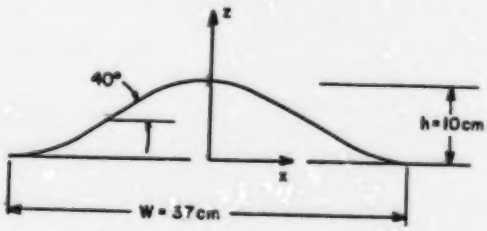
Winds near the ground are strongly influenced by the topography of the surrounding area, the stratification of the atmosphere, the diurnal heating and cooling cycle, Coriolis forces, and large-scale circulation patterns. It is difficult to consider all of these effects simultaneously and make any progress toward understanding the basic physics of the flow. However, by focusing upon one aspect at a time in controlled experiments, an understanding of the importance of the various flow phenomena can be obtained. One useful approach for studying topography and stratification effects is the testing of small-scale models in flow simulation facilities such as wind tunnels and towing tanks.

In a previous paper Lee et al. (1981) presented results from a wind tunnel study of flow over ridges and valleys under neutral atmospheric conditions when the ambient wind is at an oblique angle to the axis. The objective of the present study was to extend this work to stable conditions by conducting flow visualization experiments in a stratified towing tank. A brief description of the facility and models is presented below, followed by typical photographs and a discussion of the observed flow patterns. A more detailed description of the study is presented in Lee et al. (1984).

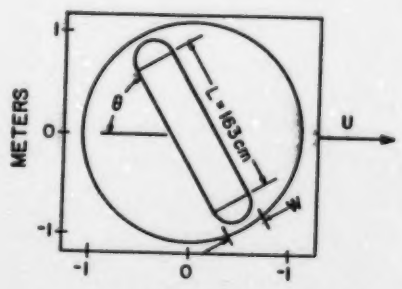
2. EXPERIMENTAL FACILITY AND MODELS

The experiments were conducted in the large stratified towing tank at the Environmental Protection Agency Fluid Modeling Facility in Research Triangle Park, North Carolina. A detailed description of this facility is presented in Hunt, Snyder, and Lawson (1978). The tank is 1.2 m deep, 2.4 m wide, and 24 m long. Arbitrary stable density profiles can be established in the tank using salt water with specific gravity of 1.0 to 1.2. Linear density profiles were used for all of the experiments in this study. The nominal value of the Brunt-Vaisala frequency, $N = [-(g/\rho)(d\rho/dz)]^{1/2}$, was 1.3 s^{-1}.

Models are mounted flush on a 2.4-m-square baseplate. The baseplate is inverted and mounted beneath a towing carriage which runs along the top of the tank. During a tow the model is upside down and completely submerged. Towing speeds can be varied from 3 to 50 cm/s. Details of the ridge model are shown in Fig. 1. It has a sinusoidal cross section given by the



(A) CROSS - SECTIONAL VIEW



(B) PLAN VIEW OF MODEL ON BASEPLATE

Fig. 1. Details of ridge model.

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relation $z = (h/2)[1 + \cos(2\pi x/W)]$. The ridge height h is 10 cm and the width W is 37 cm which results in a maximum slope of 40°. The end caps have the same sinusoidal cross section in vertical planes with a circular cross section in horizontal planes. The ridge was molded into a flat circular plate, which fits flush into the carriage baseplate so that the wind angle θ could be changed by rotating the circular plate. When the ridge is normal to the tow direction, $\theta = 90^\circ$, the minimum flow area through the gaps between the ends of the model and the walls of the tank is 25% of the cross-sectional area defined by the ridge height and the width of the tank. The valley model was constructed from two of these ridges placed together.

3. RESULTS AND DISCUSSION

A useful concept in the analysis of stable flow is the dividing streamline which separates streamlines passing over an obstacle from those which pass around the ends. The height h_s of this dividing streamline can be estimated by a simple energy argument first presented by Sheppard (1956); fluid parcels originating far upstream at an elevation above h_s have sufficient kinetic energy to pass over the top but those below h_s do not and must pass around the ends. By equating the kinetic energy of the approaching fluid at the dividing streamline elevation h_s to the increase in potential energy required to lift this fluid to the top of the hill, Sheppard derived a general formula for h_s. For an incompressible stratified fluid his result can be expressed as

$$\rho U^2(z = h_s)/2 = -g\int_{h_s}^{h} (h-z)(d\rho/dz)dz \quad , \qquad (1)$$

where h is the hill height and the density and velocity, ρ and U, are functions of the vertical coordinate z. This integral formula can be solved by iteration for h_s with arbitrary density and velocity distributions in the approach flow. For a linear density profile and a uniform velocity it can be reduced to the simple relation

$$h_s = h(1-F) \quad , \qquad (2)$$

where F is the Froude number, $F = U/Nh$. A detailed review and analysis of the theoretical and experimental basis for the dividing streamline concept is presented by Snyder et al. (1984).

In these experiments the Froude number F was varied from 0.3 to 1.0 by varying the tow velocity U from 4 to 13 cm/s. Wind angles θ of 90°, 60°, and 30° were used. Two neutral density streamers of dye were injected isokinetically from a vertical stack consisting of two small tubes attached to the leading edge of the baseplate. The ends of the tubes were bent 90° so that the dye was injected toward the model parallel to the flow, and the vertical separation between the ends of the tubes was 2 cm. The height of the stack was varied for each experiment until a position was found such that the upper dye passed over the ridge and the lower dye was blocked and diverted around the ends of the ridge. Under these conditions the dividing streamline can be regarded as being midway between the two release points with a maximum error of ±1 cm. Since the dye streamers have a finite width of approximately 1 cm when they reach the model, a more realistic estimate of the error is probably ±0.5 cm which is ±5% of the ridge height.

Photographs of the ridge model normal to the flow are presented in Fig. 2 for Froude numbers of 0.3 and 0.5 and theoretical values of h_s of 7 and 5 cm, respectively. The two dye streamers were released along the centerline of

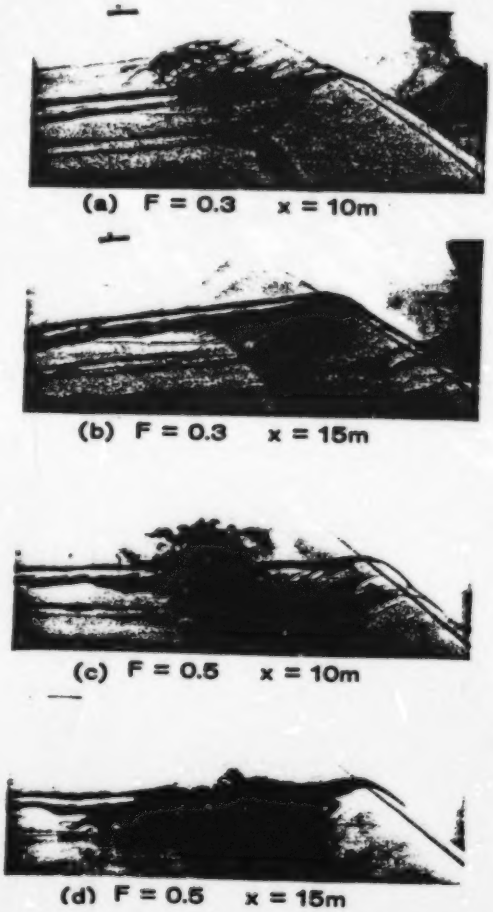

Fig. 2. Dividing streamline experiments with ridge normal to the flow, θ = 90°. Release heights = h_s ± 1 cm.

*The experimental procedures and results are discussed as though the model were in the normal upright position as opposed to the inverted position that was used during the experiments. The ambient flow is from left to right in the photographs.

the model at heights that were 1 cm above and 1 cm below the theoretical value of h_s. The photographs were taken at distances of 10 and 15 m downstream of the initial position of the model. In general the upper dye streamer passed over the ridge and the lower one was blocked. The blocked dye accumulated ahead of the ridge and flowed around either the left or right end with no obvious preference. This flow pattern switched from end to end once or twice during a tow.

For the case with a Froude number of 0.3, both dye streamers passed over the ridge near the end of the tow as shown in Fig. 2-b. This suggests that the effective Froude number of the approach flow becomes larger toward the end of the tow. This has been explained by Snyder et al. (1984) as being caused by the squashing phenomenon in which the accumulation of blocked fluid ahead of the model reduces the density gradient in a layer whose depth is the same order as the height of the model. It appears that this phenomenon is associated with the finite width of the tank and the restricted flow area through the gaps between the ends of the model and the side walls of the tank. This was investigated by conducting an experiment in which the gaps were blocked with inserts so that no flow could pass around the ends of the model. For the same conditions as in Fig. 2c-d, both of the dye streamers flowed over the model during the entire tow. An additional dye streamer was released at a lower height of 2 cm. Part of this dye flowed over the ridge, but it also accumulated in the blocked flow region ahead of the model. The flow field appeared to be unsteady during the entire run. This phenomenon has no counterpart for finite-length ridges in the atmosphere where the flow can pass around the ends or through gaps.

Data from the dividing streamline experiments with the ridge normal to the flow and with the dye released along the centerline of the model are presented in Fig 3. Open symbols indicate that the dye flowed over the top of the model and closed symbols that the dye was blocked by the model and flowed around the ends. These data are consistent with the theoretical relation $h_s/h = (1 - F)$. Observed flow patterns with a wind angle of $\theta = 60^\circ$ were similar to those with $\theta = 90^\circ$. However, the dye released below the dividing streamline flowed around the downstream end of the model during the entire tow instead of switching from end to end. The data on dividing streamline heights were very similar to those shown in Fig. 3.

With a wind angle of $\theta = 30^\circ$ there were some significant differences in the observed flow patterns. For dye released along the centerline of the model, the dividing streamline height was greater than the theoretical value given by Eq. 2. As shown in Fig. 4, these data are better described by the relation $h_s/h = (1-0.7\ F)$. However, this does not violate the dividing streamline concept which states that flow originating upstream above the theoretical value of h_s has enough kinetic energy to flow over the ridge but is not constrained to do so.

Experiments were also conducted with $\theta = 30^\circ$ and $F = 0.5$ in which dye was released from the leading edge of the baseplate at three different lateral positions. The lateral spacing between the release points was 17.5 cm with one of the streamers released along the centerline and the other two ahead of the upwind end of the ridge. When the release heights were 4 cm, none of the dye streamers flowed over the ridge as would be expected. The center streamer impinged on the model at the stagnation point, which was very near the most upwind end of the ridge. When the release heights were 6 cm, the center streamer flowed over the model and the other two flowed around opposite ends. Thus, near the stagnation point, the height of the dividing streamline is approximately 5 cm in agreement with the theory. These experiments show that the lateral position of the source relative to the stagnation point has an effect on whether a plume goes over, around, or impinges on a ridge.

In another series of experiments eleven neutral density dye streamers were released from a rake of tubes suspended from the leading edge

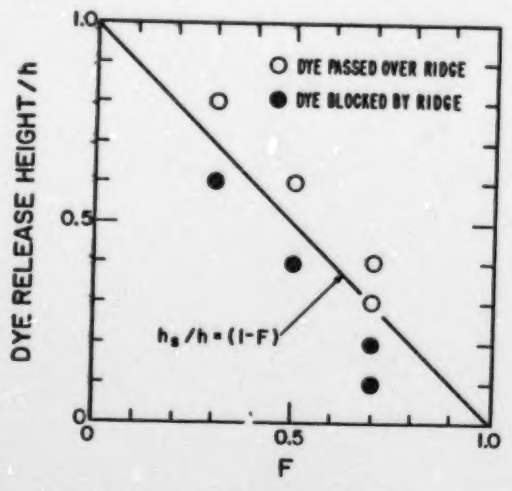

Fig. 3. Data from dividing streamline experiments for ridge normal to the flow, $\theta = 90^\circ$.

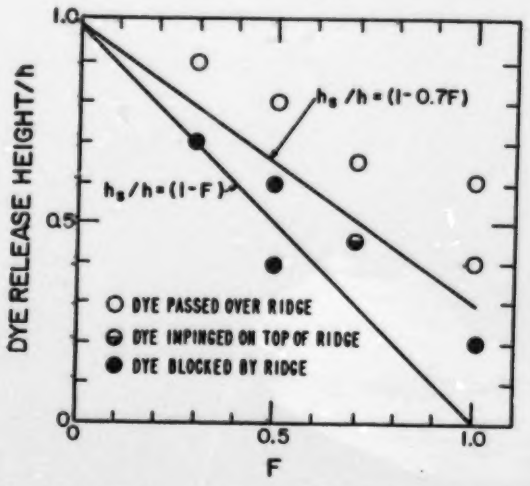

Fig. 4. Data from dividing streamline experiments for ridge with $\theta = 30^\circ$.

of the baseplate. Each tube was bent 90° toward the model and the dye was injected at a nearly isokinetic rate parallel to the ambient flow. The lowest release point was 2 cm above the base plate (0.2 h) and, with a spacing of 2 cm between tubes, the highest release point was at a height of 22 cm (2.2 h). Photographs of the ridge and valley model with a wind angle θ of 60° and a Froude number range of 0.3 to 1.7 are presented in Figs. 5 and 6.

Stratified flow over a ridge is discussed by Hunt et al. (1978). For ridges normal to the flow with rounded crests and moderate slopes, the general nature of the flow field depends primarily on the ratio of the wavelength of the lee waves, $\lambda = 2\pi U/N$, to the width of the ridge, W. This ratio can be written as $\lambda/W = 2\pi(h/W)F$ and, for the ridge used in this study, $\lambda/W = 1.7F$. When the ridge is at an angle θ to the flow, the effective width of the ridge is $W_e = W/\sin\theta$ and $\lambda/W_e = 1.7F \sin\theta$. For $\lambda \gg W_e$ ($F \gg 1$) the flow over the ridge approaches that for neutral conditions as illustrated by the streamline patterns in Fig. 5-a where $\lambda/W_e = 2.5$. Separation from the lee slope occurs near the top of the ridge and is controlled by the flow in the boundary layer. The formation and influence of the lee waves, when $\lambda/W_e = 1.3$, are apparent in Fig. 5-b where separation occurs near the downwind base of the lee slope. For $\lambda < W_e$ ($F < 0.7$), separation is controlled by the pressure distribution induced by the lee waves. This is illustrated in Fig. 5-c where separation on the lee slope is eliminated for $F = 0.5$, $\lambda/W_e = 0.75$. Under this condition a strong freestream rotor located immediately downwind of the ridge dominates the flow field. In Fig. 5-d, $\lambda/W_e = 0.44$ and separation occurs near the first trough of the lee wave, i.e., about one-third of the distance down the lee slope.

The streamline patterns over the valley model (Fig. 6) are similar to those over the ridge. Separation from the lee side of the

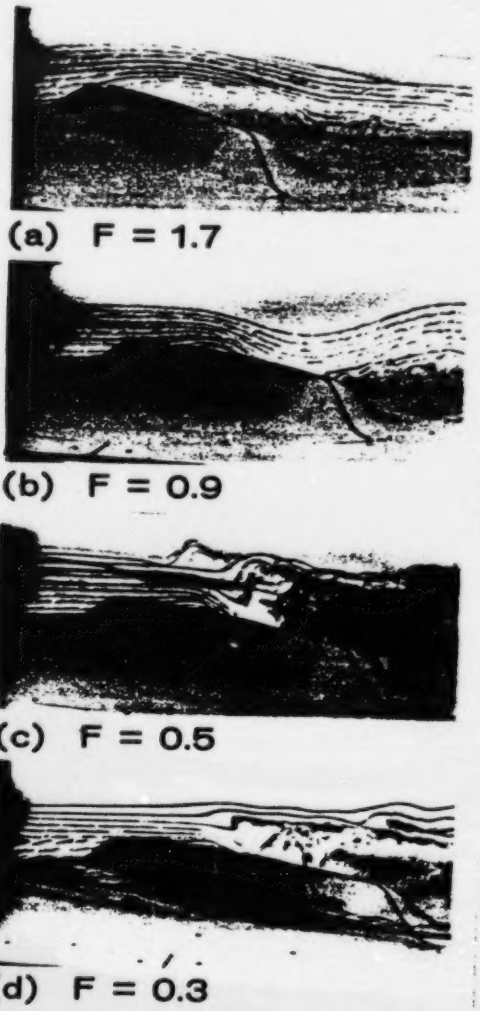

Fig. 5. Streamline pattern over center of ridge with a wind angle of θ = 60°.

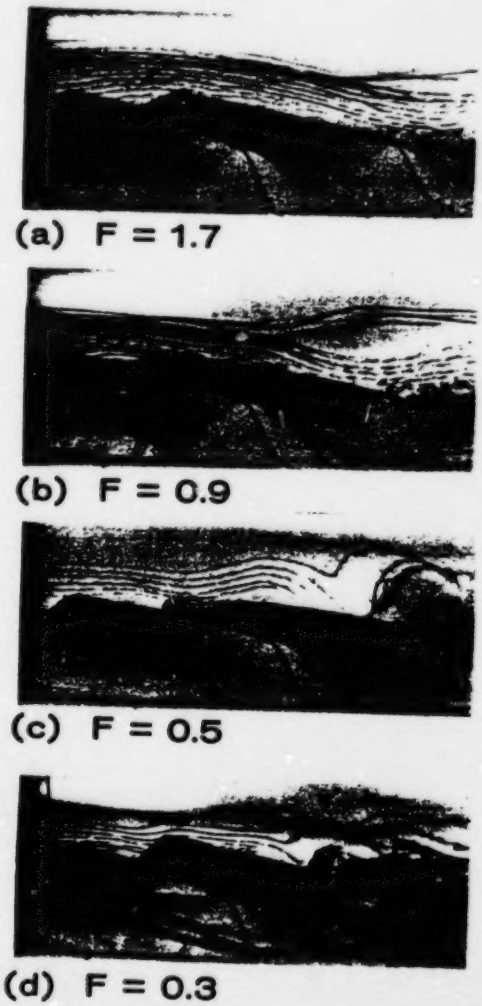

Fig. 6. Streamline pattern over center of valley with a wind angle of θ = 60°.

second ridge is eliminated for $F = 0.5$, and a strong rotor is formed downstream of the second ridge. Flow separation on the lee side of the first ridge was influenced by the lee waves, but it did not appear to be eliminated completely as on the single ridge. There appeared to be a region of separated flow between the ridges over the full range of Froude numbers, but the depth of this separated region was smaller for $F < 0.9$ than for the essentially neutral condition of $F = 1.7$.

There is no evidence in Fig. 6 of dye flowing along the valley. This is misleading, however, and results from the rapid dilution of any dye that is entrained into the separated flow in the valley. To better illustrate this entrainment, a large dye streamer was released from the leading edge of the baseplate. These photographs are shown in Fig. 7 for $F = 0.5$. In Fig. 7-a the dye was released very near the theoretical critical height h_s. Most of this dye passed over the first ridge and was trapped in the valley. It then flowed along the valley and out the downstream end. In Fig. 7-b the dye was released slightly above the critical height. It cleared both ridges of the valley and flowed into the rotor downstream of the second ridge. Thus the amount of dye which is entrained into the valley depends very strongly on the release height relative to the critical height h_s.

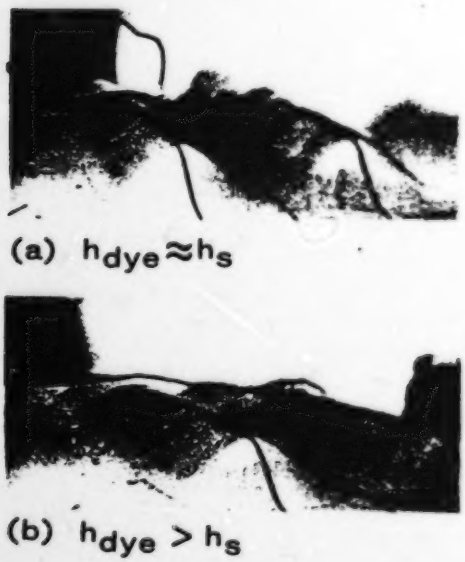

Fig. 7. Dye released near the critical height upstream of the valley with $\theta = 60^\circ$ and $F = 0.5$.

The channeling of plumes along the valley was also studied by releasing dye through the baseplate at the center of the valley floor (Lee et al., 1984). These experiments suggested that increasing stability or decreasing Froude number enhances the transport of material along a valley due to the reduced turbulent mixing between the flow in the valley and the ambient flow. This conclusion is tentative, however, since the low Froude numbers were achieved by using low velocities and, therefore, low Reynolds numbers. The experiments indicated that Reynolds number effects are not negligible for this type of separated flow under the laboratory conditions used for very low Froude numbers.

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